Testing and Characterization of PV Modules with Integrated Microinverters

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***Abstract* — Photovoltaic (PV) modules with attached microinverters are becoming increasingly popular in PV systems, especially in the residential system market, as such systems offer several benefits not found in PV systems utilizing central inverters. PV modules with fully integrated microinverters are emerging to fill a similar market space. These "AC modules" absorb solar energy and produce AC energy without allowing access to the intermediate DC bus. Existing test procedures and performance models designed for separate DC and AC components are unusable when the inverter is integrated into the module. Sandia National Laboratories is developing a new set of test procedures and performance model designed for AC modules.**

***Index Terms* — inverters, photovoltaic systems, power electronics, solar energy.**

I. INTRODUCTION

Over the past five years, PV modules equipped with microinverters have become more common in PV system installations, especially in the residential PV market. To be sure, microinverters have a lot to offer installers of small PV systems including higher MTBF, more visibility into system performance, absence of high voltage DC, and higher design flexibility. In an effort to reduce overall system costs, mechanical connections, and installation time, some manufacturers are integrating the microinverter with the PV module to create an "AC module".

To date, the characterization of a PV system equipped with microinverters requires a twofold approach: 1) characterize the performance of the PV module as a function of temperature, irradiance, spectrum, etc. and 2) characterize the microinverter performance as a function of DC voltage, power, etc. The module and inverter performance models are then operated sequentially to estimate the performance of the entire system. This typical characterization approach is not feasible for PV modules with an integrated inverter, as the DC (module) and AC (inverter) components cannot be separated without disassembly.

Sandia National Laboratories has conducted testing in an effort to characterize the entire module/microinverter system present in an "AC module". Through the testing and analysis process, Sandia will develop a method to be used by other test labs in evaluation and characterization of PV modules with fully integrated inverters. Additional testing at Sandia's Distributed Energy Technology Lab (DETL) is ongoing and will be used to ensure interoperability of many different microinverter models on the same AC circuit. Furthermore, the DETL interoperability data will be used to validate the AC module model.

II. DEFICIENCIES IN EXISTING TECHNIQUES

Sandia has a long history in developing test methods and performance models for both PV modules [1] and grid-connected PV inverters [2]-[3].

Sandia's Photovoltaic Systems Evaluation Lab (PSEL) has performed outdoor testing and evaluation services in order to develop performance parameters designed to fit the Sandia Array Performance Model (SAPM) [1]. Testing to determine SAPM performance coefficients is focused on predicting a module's current-voltage (I-V) curve over a range of irradiance and weather conditions. Characterization of the PV module requires access to the DC wires connected to the module's cells without any power conversion.

The DETL has the ability to test the performance of PV inverters according to [2] and determine inverter performance model parameters as in [3].

The separated AC and DC testing which Sandia can provide allows for the generation of two different models for performance prediction. In order to predict performance of a PV system, the models must be operated sequentially; first the module model is used to determine points on the I-V curve under a given irradiance and temperature, then the inverter model is used to predict performance given the module I-V curve.

In the case of a PV module with integrated inverter, it may be impractical or destructive to perform the necessary testing in order to generate the DC and AC models separately and thus be difficult for third parties (e.g. independent testing labs) to characterize a product's performance using existing testing techniques and predict performance using existing separate DC and AC models. It is for this reason that Sandia has chosen to develop a characterization framework specifically for systems in which the DC and AC components may not be separated.

III. TEST SETUP AND PROCEDURES

Sandia's early work included two test specimens. In order to later compare the AC-only characterization with the sequential DC and AC characterizations, the test systems employed separate (non-integrated) PV modules with a microinverter. System 1 consisted of a 180 W_P polycrystalline silicon PV module and a commercially available microinverter. System 2 consisted of a 240 W_P monocrystalline silicon PV module paired with the same microinverter. In each system, the microinverter was mounted centrally behind the module, about 2 cm away from the module back surface.

Collected weather data includes direct normal irradiance (DNI), global normal irradiance (GNI), plane of array (POA) global irradiance by reference cell and pyranometer, diffuse horizontal irradiance, wind speed and direction, ambient temperature, and many others. Module temperature was measured by thermocouples in four locations on the module back surface. Inverter temperature was measured by three thermocouples, two on the side of the inverter facing the module. AC power measurements were made by an Electro Industries Shark 100T-V3 transducer.

Testing of the "AC module" is designed to systematically isolate important characteristics which determine the performance of the module/microinverter system. Important system performance factors such as AC voltage, AC current, AC power (real, reactive, and apparent), module and inverter temperatures, and power factor are monitored under varying environmental and irradiance conditions. The initial testing process used by Sandia is founded on three separate tests.

A. Transient Thermal Testing

Thermal testing begins by cooling the module to near-ambient temperature conditions by blocking incident solar energy to the module. The test is performed under stable, clear-sky conditions. While the module is tracked normal to the sun, solar energy is reapplied and the module and inverter are allowed to heat to operating temperature. The transient thermal test attempts to extract the relationship between system power and the temperature of the components.

The transient thermal test measures the module/microinverter system's performance under a step change in irradiance. As the PV module nearly instantaneously generates current upon irradiance step changes, the transient thermal test also allows for evaluation of the inverter's turn-on time and maximum power point tracking (MPPT) speed.

B. Incident Angle Testing

Incident angle testing attempts to determine the response of the system to solar angle of incidence (AOI). The AOI response is largely dominated by the optical build of the PV module, but lower-order effects may include a change in microinverter efficiency at low DC power levels. The test is conducted under conditions with stable irradiance and spectra by varying the solar AOI from 0° to 86° with the two-axis tracker.

C. Operational Testing

Operational testing consumes the majority of the test duration. The system under test is tracked normal to the sun to eliminate incident angle effects, and the system operates normally without interference (aside from periodic cleaning). This test allows measurement of performance over a range of conditions including varying irradiances, incident spectra, ambient temperatures, wind velocities, and grid voltages. The effects of each varying condition on system performance can be extracted via multiple linear regressions of normalized performance data.

IV. Test Results and Discussion

Results, analysis descriptions, and equations provided here are our initial attempts to validate the testing method's ability to generate appropriate data to describe system performance. Full analysis procedures and predictive model are to be developed over the next year. Except where noted, results shown are from System 1 due to a complication presented by System 2, described later.

A. Transient Thermal Testing

As mentioned earlier, the thermal testing uses a shade to allow the module and inverter to cool to near-ambient temperatures. When this shade is quickly removed, a step change in irradiance is experienced. The module's DC output changes almost instantaneously, while the inverter is slower to respond as it implements its MPPT algorithm to find the module's maximum power point. As shown in Fig. 1, shade is removed at approximately 539 seconds. The co-located trigger indicator cell measures full irradiance of 1075 W/m^2 in about 2 seconds, while the microinverter reaches 90% output in 2 seconds and full power output after 4 seconds.

The relatively fast response of the microinverter to large increases in DC input power indicate that an array of modules with these microinverters would capture a large percentage of available energy under varying irradiance (e.g. sporadically cloudy) conditions. Future tests of MPPT efficiency for AC modules may involve a number of different steps in irradiance or cyclical testing, as used in [4].

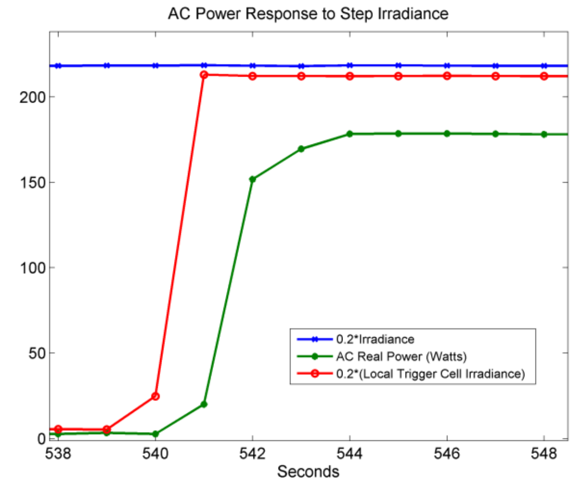

Fig. 1. AC power response to step change in irradiance.

After removal of the shade, the module and microinverter increase in temperature. As shown in Fig. 2, the module reaches operating temperature in less than 15 minutes, while the microinverter's temperature requires over an hour to stabilize.

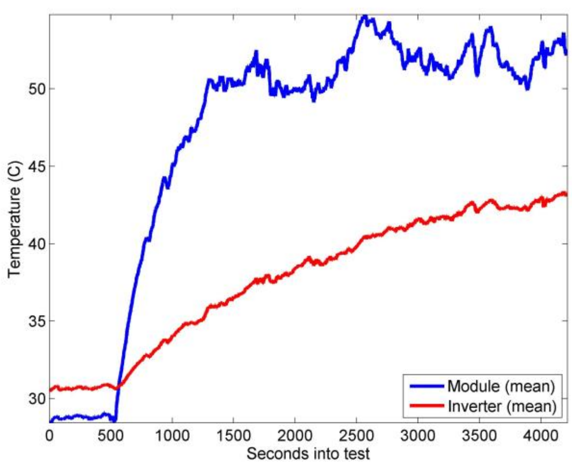

Fig. 2. Progression of temperatures during thermal test.

We suspect that the response of the module/microinverter systems to temperature is a function of both the module temperature and the microinverter temperature. However, the relative influence of each of these temperatures is unknown. As both temperatures change, the AC power output of the system also changes, even as incident irradiance remains constant. Over the duration of the test, POA irradiance changed from a minimum of 1089 W/m^2 to a maximum of 1105 W/m^2. Even though the irradiance changes less than 1.5%, the effect of these irradiance changes on power output must be removed, as shown in (1), in order to determine an approximate temperature coefficient. Note that the correction given by (1) assumes a linear response between power and irradiance. This assumption is probably acceptable for small variations in irradiance observed in the thermal testing, but may be inadequate to describe larger irradiance variations. A more complex irradiance/power relationship may be determined through subsequent testing. The changes in temperature-corrected power as a function of both module temperature and inverter temperature are shown in Fig. 3.

$$P_{corrected} = P_{meas} * E_0 / E \qquad (1)$$

where:

$P_{corrected}$ is the AC power corrected for irradiance variations
P_{meas} is the measured AC power
E_0 is a reference irradiance (e.g. 1000 W/m^2)
E is the measured plane of array irradiance

It can clearly be seen from Fig. 3 that module temperature dominates the temperature performance of the system and, as is expected, higher module temperatures yield lower power output. A close examination of Fig. 3 also shows that higher inverter temperatures yield lower power output, although the influence is much smaller than the influence of module temperature.

Since module temperature appears to be the dominant temperature effect, we have plotted the performance as a function of only module temperature and determined a system AC power temperature coefficient of approximately -0.43 %/C_{Tmod} as shown in Fig. 4.

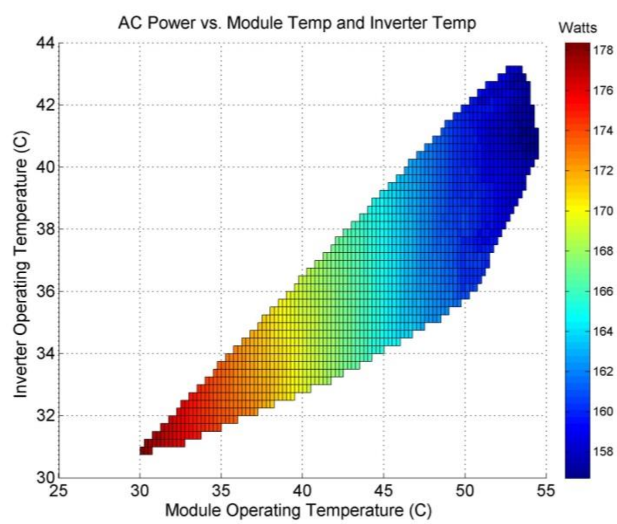

Fig. 3. Irradiance-corrected AC power as a function of module and inverter temperature.

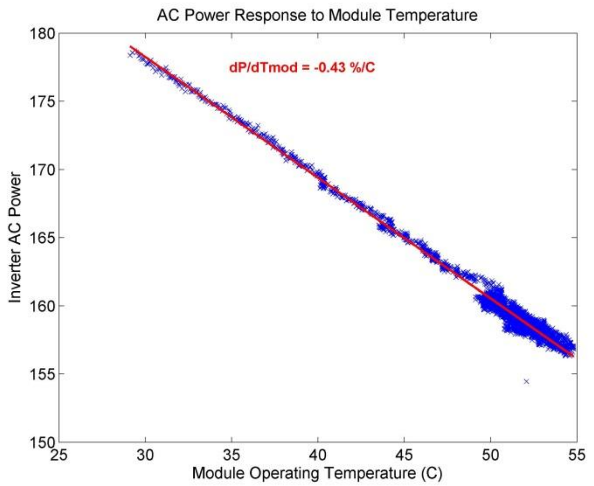

Fig. 4. Irradiance-corrected AC Power as a function of module temperature.

B. Incident Angle Testing

After the transient thermal test has been completed, the effect of varying temperature may be mitigated in future testing. This is necessary in the incident angle test; as the module is stepped through a fixed set of incident angles, the temperature of the module is typically reduced at high AOI, as shown in Fig. 5.

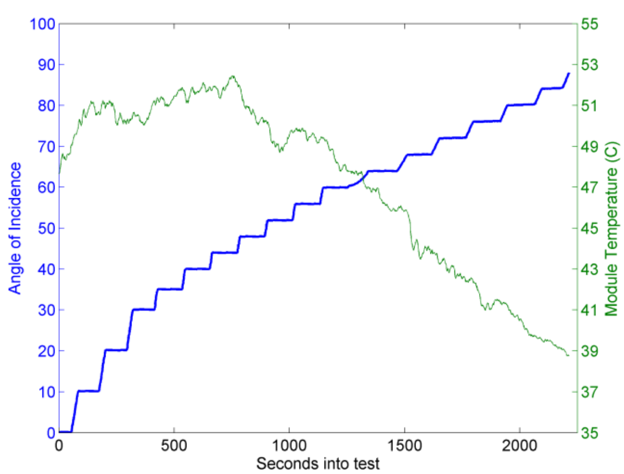

Fig. 5. AOI and module temperature during incident angle testing.

The AC power measured over the incident angle test may be normalized for variations in module temperature and irradiance (assuming the same power/irradiance linearity) through (2).

$$P_{AOInorm} = \frac{P_{meas} * E_0 / \{P_{ref} * [1 + \gamma_{Tm} * (T_m - T_0)]\} - E_{diffuse}}{E_{beam}} \quad (2)$$

where:

P_{ref} is the normalized power when AOI=0
γ_{Tm} is the temperature coefficient of the power as a function of module temperature in units of 1/C
T_m is the mean module temperature
T_0 is a reference module temperature (e.g. 25 C)
$E_{diffuse}$ is the plane-of-array diffuse irradiance
E_{beam} is the plane-of-array beam irradiance

If $P_{AOInorm}$ is plotted as a function of AOI as shown in Fig. 6, the incident angle response of the system, excluding cosine loss effects, can be determined. In this case, the AOI response is approximated with a 5th order polynomial. The polynomial, or any arbitrary function describing this behavior, describes the amount of beam irradiance which passes through module's front surface to generate power at a given incident angle.

The response of the system to incident angle is similar to comparable responses which Sandia determines in testing PV modules from their I-V curves. This is as expected, since the module is the only device in the system which responds to incident beam irradiance. The similarities give confidence that it is possible to determine AOI response of the module, even when the module is integrated with a microinverter.

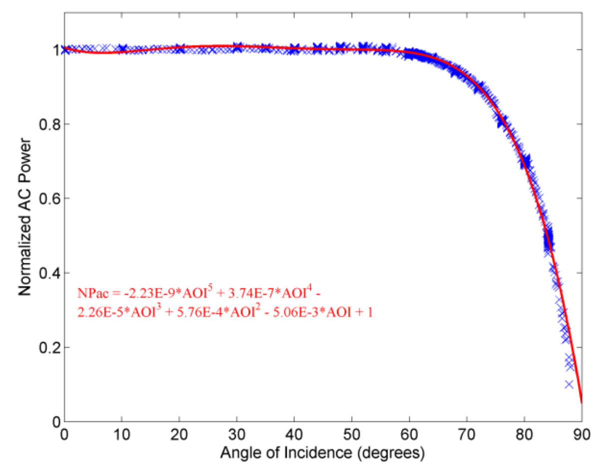

Fig. 6. System response to incident angle, fit with a polynomial.

C. Operational Testing

In operational testing, tracking the AC module normal to the sun eliminates incident angle effects; and through the use of the previously determined temperature coefficient, effects due to variations in module temperature may be removed. The operational testing results can then be analyzed to show the response of the system to incident irradiance, incident spectra, wind speed, ambient temperature, or other environmental factors. These analyses may reveal a more complex power/irradiance relationship than the linear relationship assumed in (1) and (2).

For example, if conditions are limited to only stable and clear skies (e.g. DNI/GNI > 0.87), then absolute airmass can be used as a simple-to-calculate proxy for incident spectra. A correction, much like (1), is shown in (3) with the inclusion of the module temperature coefficient. When the data is correspondingly limited to clear conditions, and P_{AMcorr} is plotted as a function of absolute airmass, we obtain Fig. 7.

$$P_{AMcorr} = \frac{P_{meas} * E_0}{\left[1 + \gamma_{Tm} * \left(T_m - T_0\right)\right] * E} \tag{3}$$

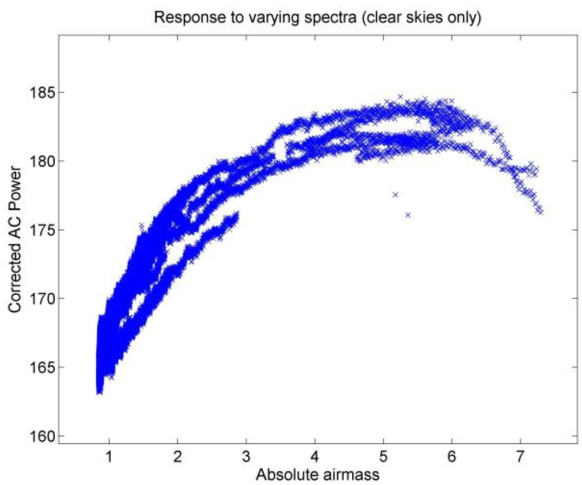

Fig. 7. Temperature and irradiance corrected AC power as a function of airmass.

The power/airmass relationship shown in Fig. 7 bears a striking resemblance to a similar relationship used in the Sandia Photovoltaic Array Performance Model (SAPM) [1] which describes airmass response for other polycrystalline silicon PV modules. Thus, we believe that a power/airmass relationship may be determined for AC modules in much the same fashion as the relationship can be determined for PV modules alone. Likewise, we also believe that appropriate testing and analysis can determine other performance-influencing factors for full characterization of an AC module.

The "operational testing" also found a potential difficulty in characterizing AC modules, caused by the power-limiting (curtailing or "clipping") of the inverter. Designers of PV modules with either integrated microinverters or separate microinverters may oversize the module for the inverter (i.e. use a high DC/AC rating ratio). The combination of a PV module with nominal power at or above the nominal power rating of the microinverter causes a large number of times where the inverter must limit the power output of the system, namely during times of high POA irradiance. Fig. 8 shows the relationship between POA irradiance (from a thermopile pyranometer) and the measured AC power from System 1, wherein the module was undersized for the inverter with a DC/AC ratio less than 0.85 and slightly below the range suggested by the inverter manufacturer. Fig. 9 shows the same relationship for System 2, where the DC/AC ratio was over 1, within the range recommended by the inverter manufacturer. In both figures, each point is colored according to the ratio of direct normal irradiance (DNI) to global normal irradiance (GNI), thus indicating the direct/diffuse conditions present at the time of the measurement.

The power limiting shown in fig. 9 presents a non-linearity in the performance of the AC module system. As one would expect, the non-linearity is also present in plots of power as a function of temperature, incident angle, airmass, etc. and introduces some difficulty in isolating parameters. Methods to mitigate the effects of inverter power limiting are under consideration at Sandia, and will be developed and presented in future work.

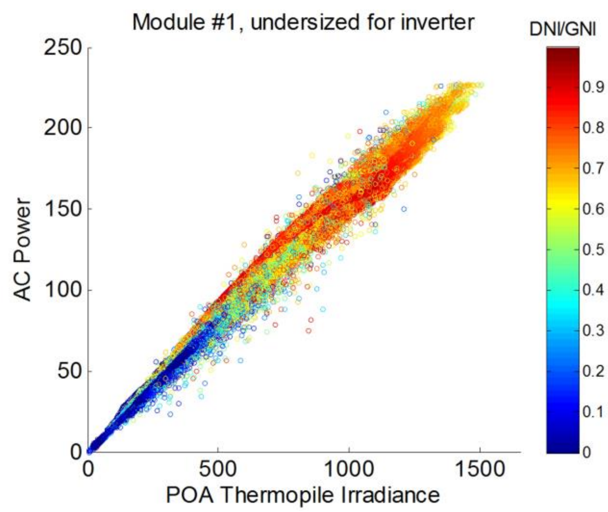

Fig. 8. System 1 measured AC power with irradiance, colored for DNI/GNI ratio.

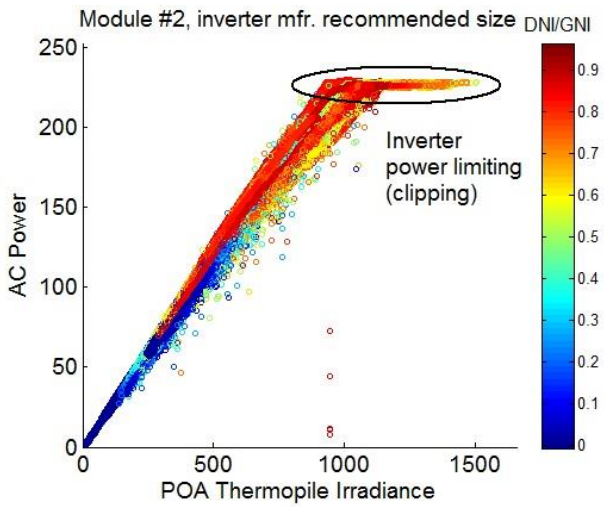

Fig. 9. System 2 measured AC power with irradiance, colored for DNI/GNI ratio.

V. Conclusion and Future Work

As PV arrays utilizing microinverters have become more common, especially in residential and small commercial applications, we believe that future market growth may utilize modules with integrated microinverters. Sandia National Laboratories is developing a method for testing and analyzing these AC modules to characterize their performance in a range of operating conditions. These efforts are an extension of Sandia's prior work in characterizing PV modules and PV inverters [1]-[3].

Sandia has recently tested two systems of PV modules with microinverters in lieu of a true AC module with integrated microinverters. The testing provides a set of foundational data upon which to build a characterization method. The test methods used to gather the initial data set may also need to be refined in order to better isolate the performance parameters of interest.

The initial test data indicates that it is possible to isolate performance-affecting factors using only the AC output of the microinverter. In particular, early analysis shows that temperature coefficient, airmass response, incident angle response, and inverter turn-on time are able to be determined from test data. We also believe that other factors such as the irradiance/power relationship and power level at which the inverter curtails can be determined from the test data.

Sandia will continue developing a testing, analysis, and characterization framework to better predict the performance of AC modules. This will first entail testing a larger variety of systems, refining the test processes, development of a more robust and complex analysis process including data filtering, identification of the most influential factors on system performance, and synthesizing the influential factors into a characterization framework capable of predicting performance.

Acknowledgement

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